

What is claimed is:

1 1. A phase and frequency tracking apparatus for multi-
2 carrier systems, comprising:
3 an *m*th-order tracking loop for computing a phase
4 tracking value, a normalized frequency tracking
5 value and a normalized acceleration tracking
6 value for a current symbol based on a phase
7 estimate of said current symbol and a plurality
8 of loop parameters;
9 a frequency predictor for calculating as output a
10 feedback compensation frequency for a next symbol
11 based on an equivalent feedback delay, said
12 normalized frequency tracking value and said
13 normalized acceleration tracking value of said
14 current symbol; and
15 a pre-DFT synchronizer for compensating the phase and
16 frequency of a received signal in a time domain
17 using said feedback compensation frequency before
18 taking an *N*-point Discrete Fourier Transform
19 (DFT).

1 2. The apparatus as recited in claim 1 wherein said
2 *m*th-order tracking loop is a third-order tracking loop
3 modeled with a set of recursive equations, as follows:

$$\begin{aligned}\phi_{T,i} &= \phi_{P,i} + \mu_{\phi,i} \phi_{\epsilon,i} \\ \Omega_{T,i} &= \Omega_{P,i} + \mu_{f,i} \phi_{\epsilon,i} \\ a_{T,i} &= a_{T,i-1} + \mu_{a,i} \phi_{\epsilon,i}\end{aligned}$$

5 and

$$\begin{aligned}\phi_{P,i+1} &= \phi_{T,i} + \Omega_{T,i} \\ \Omega_{P,i+1} &= \Omega_{T,i} + a_{T,i}\end{aligned}$$

where

subscript i denotes a symbol index,

$\phi_{T,i}$, $\Omega_{T,i}$ and $a_{T,i}$ respectively denote said phase, said normalized frequency and said normalized acceleration tracking values of symbol i ,

$\mu_{\phi,i}$, $\mu_{f,i}$ and $\mu_{a,i}$ respectively denote said loop parameters of the i th symbol for $\phi_{T,i}$, $\Omega_{T,i}$ and $a_{T,i}$,

$\phi_{P,i}$ and $\Omega_{P,i}$ respectively denote a phase prediction value and a normalized frequency prediction value of the i th symbol,

$\phi_{P,i+1}$ and $\Omega_{P,i+1}$ are said phase and said normalized frequency prediction values of symbol $i+1$,

$a_{T,i-1}$ is said normalized acceleration tracking value of symbol $i-1$,

and $\phi_{e,i}$, a phase prediction error of the i th symbol, is given by:

$$\phi_{e,i} = \phi_{E,i} - \phi_{P,i}$$

where $\phi_{E,i}$ denotes said phase estimate of the i th symbol.

3. The apparatus as recited in claim 2 wherein initial values of said phase, said normalized frequency and said normalized acceleration tracking values, $\phi_{T,i}$, $\Omega_{T,i}$ and $a_{T,i}$, are set to zero, for $i=-1$; said loop parameters $\mu_{f,i}$ and $\mu_{a,i}$ are equal to zero, for $i=0$.

4. The apparatus as recited in claim 2 wherein said feedback compensation frequency is calculated for said next symbol from:

4 $\Omega_{C,i+1} = \Omega_{T,i} + D_f a_{T,i}$
5 where D_f is a numerical representation of said equivalent
6 feedback delay and $\Omega_{C,i+1}$ is said feedback compensation
7 frequency of symbol $i+1$.

1 5. The apparatus as recited in claim 1 wherein said
2 pre-DFT synchronizer receives said feedback compensation
3 frequency of the i th symbol, $\Omega_{C,i}$, to compensate the
4 frequency of said received signal and de-rotate the phase of
5 said received signal in the time domain before taking the
6 N -point DFT, by:

7
$$\tilde{r}_i[n] = r_i[n] e^{j\Omega_{C,i} \frac{(N-1)-2n}{2N'}}, \quad 0 \leq n \leq N-1$$

8 where n denotes a sample index, $r_i[n]$ denotes said received
9 signal of sample n of symbol i , and N' is the number of
10 samples in a symbol interval.

1 6. A phase and frequency tracking apparatus for multi-
2 carrier systems, comprising:

3 an m th-order tracking loop for computing a phase
4 tracking value, a normalized frequency tracking
5 value and a normalized acceleration tracking
6 value for a current symbol based on a phase
7 estimate of said current symbol and a plurality
8 of loop parameters, wherein said phase tracking
9 value is employed to compensate for an effect of
10 phase drift; and

11 a frequency predictor for calculating as output a
12 feedback compensation frequency for a next symbol
13 based on an equivalent feedback delay, said
14 normalized frequency tracking value and said

15 normalized acceleration tracking value of said
16 current symbol, whereby pre-DFT synchronization
17 can be accomplished using said feedback
18 compensation frequency.

1 7. The apparatus as recited in claim 6 wherein said
2 phase estimate of said current symbol, $\phi_{E,i}$, is computed from
3 the following function:

$$4 \quad \phi_{E,i} = \text{angle} \left(\sum_{m=1}^{N_{SP}} R'_{i,p_m} (H_{p_m} X_{i,p_m})^* \right)$$

5 where

6 superscript * denotes complex conjugation,
7 subscript i denotes a symbol index,
8 N_{SP} is the number of the pilot subcarriers,
9 subscript p_m denotes a pilot subcarrier index, for
10 $m = 1, \dots, N_{SP}$,
11 H_{p_m} denotes said channel response of pilot subcarrier
12 p_m ,
13 X_{i,p_m} denotes said transmitted data on pilot subcarrier
14 p_m of symbol i ,
15 R'_{i,p_m} denotes said timing compensated version of the i th
16 symbol on pilot subcarrier location p_m , and
17 $\phi_{E,i}$ represents said phase estimate of the i th symbol.

1 8. The apparatus as recited in claim 6 wherein said
2 m th-order tracking loop is a third-order tracking loop
3 modeled with a set of recursive equations, as follows:

$$4 \quad \begin{aligned} \phi_{T,i} &= \phi_{P,i} + \mu_{\phi,i} \phi_{E,i} \\ \Omega_{T,i} &= \Omega_{P,i} + \mu_{f,i} \phi_{E,i} \\ a_{T,i} &= a_{T,i-1} + \mu_{a,i} \phi_{E,i} \end{aligned}$$

5 and

$$\begin{aligned} \phi_{P,i+1} &= \phi_{T,i} + \Omega_{T,i} \\ \Omega_{P,i+1} &= \Omega_{T,i} + a_{T,i} \end{aligned}$$

where

subscript i denotes a symbol index,

$\phi_{T,i}$, $\Omega_{T,i}$ and $a_{T,i}$ respectively denote said phase, said normalized frequency and said normalized acceleration tracking values of symbol i ,

$\mu_{\phi,i}$, $\mu_{f,i}$ and $\mu_{a,i}$ respectively denote said loop parameters of the i th symbol for $\phi_{T,i}$, $\Omega_{T,i}$ and $a_{T,i}$,

$\phi_{P,i}$ and $\Omega_{P,i}$ respectively denote a phase prediction value and a normalized frequency prediction value of the i th symbol,

$\phi_{P,i+1}$ and $\Omega_{P,i+1}$ are said phase and said normalized frequency prediction values of symbol $i+1$,

$a_{T,i-1}$ is said normalized acceleration tracking value of symbol $i-1$,

and $\phi_{\varepsilon,i}$, a phase prediction error of the i th symbol, is given by:

$$\phi_{\varepsilon,i} = \phi_{E,i} - \phi_{P,i}$$

where $\phi_{E,i}$ denotes said phase estimate of the i th symbol.

9. The apparatus as recited in claim 8 wherein initial values of said phase, said normalized frequency and said normalized acceleration tracking values, $\phi_{T,i}$, $\Omega_{T,i}$ and $a_{T,i}$, are set to zero, for $i=-1$; said loop parameters $\mu_{f,i}$ and $\mu_{a,i}$ are equal to zero, for $i=0$.

10. The apparatus as recited in claim 8 wherein said feedback compensation frequency is calculated for said next symbol from:

4 $\Omega_{C,i+1} = \Omega_{T,i} + D_f a_{T,i}$
5 where D_f is a numerical representation of said equivalent
6 feedback delay and $\Omega_{C,i+1}$ is said feedback compensation
7 frequency of symbol $i+1$.

1 11. The apparatus as recited in claim 6 wherein said
2 feedback compensation frequency of the i th symbol, $\Omega_{C,i}$, is
3 provided as feedback to de-rotate a received signal prior to
4 taking the N -point DFT, by:

$$5 \quad \tilde{r}_i[n] = r_i[n] e^{j\Omega_{C,i} \frac{(N-1)-2n}{2N'}}, \quad 0 \leq n \leq N-1$$

6 where n denotes a sample index, $r_i[n]$ denotes said received
7 signal of sample n of symbol i , and N' is the number of
8 samples in a symbol interval.

1 12. A phase and frequency drift compensation apparatus
2 for multi-carrier systems, comprising:

3 a timing offset compensator for receiving a current
4 symbol in a frequency domain after taking an N -
5 point Discrete Fourier Transform (DFT) and
6 compensating for a timing offset in said current
7 symbol;

8 a phase estimator for taking a timing compensated
9 version of said current symbol on pilot
10 subcarrier locations and computing a phase
11 estimate for said current symbol based on a
12 function of a channel response of each pilot
13 subcarrier, transmitted data on each pilot
14 subcarrier, and said timing compensated version
15 of said current symbol on said pilot subcarrier
16 locations;

17 an m th-order tracking loop for computing a phase
18 tracking value, a normalized frequency tracking
19 value and a normalized acceleration tracking
20 value for said current symbol based on said phase
21 estimate of said current symbol and a plurality
22 of loop parameters;
23 a frequency predictor for calculating as output a
24 feedback compensation frequency for a next symbol
25 based on an equivalent feedback delay, said
26 normalized frequency tracking value and said
27 normalized acceleration tracking value of said
28 current symbol;
29 a pre-DFT synchronizer for compensating the phase and
30 frequency of a received signal in a time domain
31 using said feedback compensation frequency before
32 taking the N -point DFT; and
33 a phase compensator for compensating said timing
34 compensated version of said current symbol for an
35 effect of phase drift with said phase tracking
36 value of said current symbol.

1 13. The apparatus as recited in claim 12 wherein said
2 m th-order tracking loop is a third-order tracking loop
3 modeled with a set of recursive equations, as follows:

$$\begin{aligned}\phi_{T,i} &= \phi_{P,i} + \mu_{\phi,i} \phi_{\epsilon,i} \\ \Omega_{T,i} &= \Omega_{P,i} + \mu_{f,i} \phi_{\epsilon,i} \\ a_{T,i} &= a_{T,i-1} + \mu_{a,i} \phi_{\epsilon,i}\end{aligned}$$

5 and

$$\begin{aligned}\phi_{P,i+1} &= \phi_{T,i} + \Omega_{T,i} \\ \Omega_{P,i+1} &= \Omega_{T,i} + a_{T,i}\end{aligned}$$

7 where

8 subscript i denotes a symbol index,

9 $\phi_{T,i}$, $\Omega_{T,i}$ and $a_{T,i}$ respectively denote said phase, said
10 normalized frequency and said normalized
11 acceleration tracking values of symbol i ,

12 $\mu_{\phi,i}$, $\mu_{f,i}$ and $\mu_{a,i}$ respectively denote said loop
13 parameters of the i th symbol for $\phi_{T,i}$, $\Omega_{T,i}$ and $a_{T,i}$,

14 $\phi_{P,i}$ and $\Omega_{P,i}$ respectively denote a phase prediction
15 value and a normalized frequency prediction value
16 of the i th symbol,

17 $\phi_{P,i+1}$ and $\Omega_{P,i+1}$ are said phase and said normalized
18 frequency prediction values of symbol $i+1$,

19 $a_{T,i-1}$ is said normalized acceleration tracking value of
20 symbol $i-1$,

21 and $\phi_{e,i}$, a phase prediction error of the i th symbol, is given
22 by:

23
$$\phi_{e,i} = \phi_{E,i} - \phi_{P,i}$$

24 where $\phi_{E,i}$ denotes said phase estimate of the i th symbol.

1 14. The apparatus as recited in claim 13 wherein
2 initial values of said phase, said normalized frequency and
3 said normalized acceleration tracking values, $\phi_{T,i}$, $\Omega_{T,i}$ and
4 $a_{T,i}$, are set to zero, for $i=-1$; said loop parameters $\mu_{f,i}$ and
5 $\mu_{a,i}$ are equal to zero, for $i=0$.

1 15. The apparatus as recited in claim 13 wherein said
2 feedback compensation frequency is calculated for said next
3 symbol from:

4
$$\Omega_{C,i+1} = \Omega_{T,i} + D_f a_{T,i}$$

5 where D_f is a numerical representation of said equivalent
6 feedback delay and $\Omega_{C,i+1}$ is said feedback compensation
7 frequency of symbol $i+1$.

1 16. The apparatus as recited in claim 12 wherein said
2 pre-DFT synchronizer receives said feedback compensation
3 frequency of the i th symbol, $\Omega_{C,i}$, to compensate the
4 frequency of said received signal and de-rotate the phase of
5 said received signal in the time domain before taking the
6 N -point DFT, by:

$$7 \quad \tilde{r}_i[n] = r_i[n] e^{j\Omega_{C,i} \frac{(N-1)-2n}{2N'}}, \quad 0 \leq n \leq N-1$$

8 where n denotes a sample index, $r_i[n]$ denotes said received
9 signal of sample n of symbol i , and N' is the number of
10 samples in a symbol interval.

1 17. The apparatus as recited in claim 12 wherein said
2 phase estimator computes said phase estimate of said current
3 symbol, $\phi_{E,i}$, by means of the following function:

$$4 \quad \phi_{E,i} = \text{angle} \left(\sum_{m=1}^{N_{SP}} R'_{i,p_m} (H_{p_m} X_{i,p_m})^* \right)$$

5 where

6 superscript $*$ denotes complex conjugation,

7 subscript i denotes a symbol index,

8 N_{SP} is the number of the pilot subcarriers,

9 subscript p_m denotes a pilot subcarrier index, for

10 $m = 1, \dots, N_{SP}$,

11 H_{p_m} denotes said channel response of pilot subcarrier

12 p_m ,

13 X_{i,p_m} denotes said transmitted data on pilot subcarrier
14 p_m of symbol i ,
15 R'_{i,p_m} denotes said timing compensated version of the i th
16 symbol on pilot subcarrier location p_m , and
17 $\phi_{E,i}$ represents said phase estimate of the i th symbol.

1 18. A phase and frequency tracking apparatus for multi-
2 carrier systems, comprising:

3 a pre-DFT synchronizer for compensating the phase and
4 frequency of a received signal in a time domain
5 using a feedback compensation frequency before
6 taking an N -point Discrete Fourier Transform
7 (DFT).

1 19. The apparatus as recited in claim 18 wherein said
2 pre-DFT synchronizer receives said feedback compensation
3 frequency of the i th symbol, $\Omega_{C,i}$, to compensate the
4 frequency of said received signal and de-rotate the phase of
5 said received signal in the time domain before taking the
6 N -point DFT, by:

7
$$\tilde{r}_i[n] = r_i[n] e^{j\Omega_{C,i} \frac{(N-1)-2n}{2N'}}, \quad 0 \leq n \leq N-1$$

8 where n denotes a sample index, $r_i[n]$ denotes said received
9 signal of sample n of symbol i , and N' is the number of
10 samples in a symbol interval.